

LOCAL VAPOR FUEL CELL

Patent Application of
Laixia Yang and Wen C. Huang

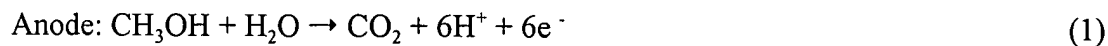
FIELD OF THE INVENTION

This invention relates to a fuel cell operating on a hydrogen-rich organic fuel that is initially in a liquid form directly fed via diffusion into the anode; but the fuel turns into a vapor form when it comes in contact with the catalyst phase in the anode. The diffusion process is preferably driven by a capillarity force without using a liquid delivery pump. The invention specifically relates to a local vapor fuel cell (LVFC) such as a methanol vapor fuel cell (MVFC) or ethanol vapor fuel cell (EVFC).

BACKGROUND OF THE INVENTION

A fuel cell is a device which converts the chemical energy into electricity. A fuel cell differs from a battery in that the fuel and oxidant of a fuel cell are supplied from sources that are external to the cell, which can generate power as long as the fuel and oxidant are supplied. A particularly useful fuel cell for powering portable electronic devices is a direct methanol fuel cell (DMFC) in which the fuel is a liquid methanol/water mixture and the oxidant is air or oxygen. Protons are formed by oxidation of methanol and water at the anode (fuel electrode) and pass through a proton-exchange membrane (or polymer electrolyte membrane, PEM) from the anode to the cathode (oxidant electrode). Electrons produced at the anode in the oxidation reaction flow in the external circuit to the cathode, driven by the difference in electric potential between the anode and cathode and can therefore do useful work.

The electrochemical reactions occurring in a direct methanol fuel cell which contains an acid electrolyte are:



1 The DMFC and other proton-exchange membrane fuel cells (PEMFCs) use a hydrated
sheet of a perfluorinated acid-based ionomer membrane as a solid electrolyte. The electrodes
each typically containing a catalyst phase (usually a thin catalyst layer) are intimately bonded to
each side of the membrane. This membrane is commercially available from either DuPont (under
the trade name Nafion[®]) or from Dow Chemical. Many catalysts to promote methanol oxidation
6 (Reaction 1) have been evaluated. Examples include: (1) noble metals, (2) noble metal alloys,
(3) alloys of noble metals with non-noble metals, (4) chemisorbed layers on Pt, (5) platinum with
inorganic material, and (6) redox catalysts. Based on literature reports, Pt-Ru appears to be the
best methanol-oxidation catalyst in acidic electrolytes.

11 The methanol/water feed to a DMFC may be in the liquid or vapor phase. If fuel cells
using liquid fuel are available in small size, they would be able to power small-sized electronic
devices for a long time. However, conventional DMFCs require pumps and blowers to feed
liquid fuel to the fuel cell (e.g., S. Surampudi, et al., U.S. Pat. No. 6,248,460, June 19, 2001).
The resulting power system is complex in structure and large in size. One way to overcome this
problem is to utilize capillary action to feed liquid fuel, without using a liquid delivery pump.

16 However, a fuel cell of this type still has the following disadvantages: (1) poor
performance due to low electrode reactivity and (2) low fuel utilization efficiency due to
methanol cross-over from the anode through the electrolyte membrane to the cathode. This
problem of methanol crossing over without being reacted is relatively more severe in a fuel cell
with a pressurizing pump than in one without a pump.

21 It is believed that methanol vapor cells that operate at higher temperatures are
advantageous in that the step of methanol ionization to produce protons (e.g., Reaction (1))
proceeds more rapidly in these cells (e.g., as suggested in A. A. Kulikovsky, et al. "Two-
dimensional simulation of direct methanol fuel cell," in Journal of the Electrochemical Society,
147 (3) (2000) 953-959). Presumably, a higher temperature results in a higher catalytic electrode
26 activity and the faster reaction leads to a reduction in fuel cross-over. However, in the
conventional DMFC of a vapor feed type, methanol (as a liquid fuel) is introduced by a pump

1 into a vaporizer which vaporizes methanol with the resulting methanol vapor then being fed to
the fuel cell by a blower. Unconsumed methanol vapor discharged from the outlet of the fuel
electrode is recycled to the methanol tank through a condenser. This process needs a complex
system (including a pump, a vaporizer, a blower, and a condenser) and, hence, is not suitable for
powering small-sized electronic devices.

6 Tomimatsu, et al. (U.S. Pat. No. 6,447,941, Sep. 10, 2002) disclosed a fuel cell in the
form of stacked unit cells each having a power generating section composed of a fuel electrode,
an oxidant electrode, and an electrolyte plate held therebetween. The unit cells are placed on top
of one another. In this fuel cell, a liquid fuel is introduced into each unit cell by the capillary
action and evaporated in each unit cell in a fuel evaporating layer, so that the fuel electrode is
11 supplied with the evaporated fuel. This is a very interesting fuel cell design since it makes use of
the two sound approaches: liquid feed by capillary action and vapor state reaction. However, the
fuel cell configuration is still too complex since each unit cell contains, among other layers,
separate anode, liquid-permeating, and fuel evaporating layers. Too many layers make the fuel
cell more tedious to make and more costly.

16 One object of the present invention is to provide a simpler configuration for a fuel cell
that operates primarily on an organic fuel vapor. A specific object of the present invention is to
provide a fuel cell that operates on a diffusion-fed methanol/water liquid fuel, which is then
vaporized *in situ* at or near the anode catalyst prior to being ionized to produce protons.

21 From a systems standpoint, fuel cell operation on liquid methanol-water mixture
containing some of the corresponding vapor is more advantageous. Therefore, another object of
the present invention is to provide a fuel cell that operates on an organic fuel such as methanol
that is at least partially vaporized when in contact with the anode catalyst.

BRIEF SUMMARY OF THE INVENTION

26 The present invention provides a light-weight, compact fuel cell that is well-suited to
powering portable electronic devices. The invented local vapor fuel cell (LVFC) is composed of

1 one or several unit cells that are physically stacked together and are electrically connected in
series to provide a desired voltage level. Each unit cell comprises (A) an anode receiving a
liquid fuel from a liquid fuel source substantially through diffusion; (B) an electrolyte plate (or
proton exchange membrane, PEM) having a first surface adjacent to the anode; and (C) a cathode
adjacent to a second surface of the electrolyte plate and opposite to the anode. The anode is
6 provided with a heating environment to at least partially vaporize the liquid fuel inside the anode
to produce fuel vapor near or at the catalyst phase. The catalyst phase ionizes the fuel vapor or
the vapor-liquid mixture to produce protons that migrate through the PEM (e.g., a polymer
electrolyte membrane) to the cathode side. The catalyst phase preferably forms a thin layer
adjacent to the electrolyte plate.

11 A special feature of the presently invented LVFC is that the fuel (e.g., methanol/water
mixture) is supplied initially in a liquid form into the anode primarily via diffusion, preferably
under the action of a capillary force. To accomplish this function, the anode may be made to
comprise a porous fuel-permeating material being in fluid communication with a liquid fuel
source and receiving the liquid fuel therefrom. However, the liquid fuel is vaporized, partially or
16 completely, just before or when it comes in contact with a catalyst. This heated environment
allows the fuel vapor or vapor-liquid mixture to react at a higher temperature in a more efficient
manner for proton generation. The heating environment may receive the heat generated by the
electrochemical reactions occurring at the cathode. Alternatively or additionally, the heating
environment may receive the heat from joule heating by passing a current through the anode.
21 This current may flow through a thin wire that is preferably localized in the vicinity of the
catalyst phase. The current may be provided intermittently on demand with the assistance of a
temperature sensor and a control circuit. Other preferred embodiments of the present invention
include several configurations of multiple-cell fuel cell devices with each of these cells
exhibiting the aforementioned features.

26 The LVFC that relies on a heating element to provide additional heat to help locally
vaporize the liquid fuel at the anode catalyst phase is hereinafter referred to as an extrinsically
controlled LVFC or actively controlled LVFC. The FVFC that relies primarily on the internally

1 generated heat due to electrode reactions is referred to as an intrinsically controlled LVFC or
passively controlled LVFC. The advantages of such an extrinsically controlled LVFC includes:

- 6 (1) The amount of electrical power needed to generate the local joule heat represents only a
very small fraction of the total amount of power that a fuel cell can provide. The resulting
improvement in the power output considerably more than compensates for the power loss
that is required to locally vaporize the fuel.
- 11 (2) Since the heat is generated locally to vaporize the liquid fuel near the anode, there is very
little heat loss to the outside environment. By contrast, the current direct methanol fuel
cell of a direct vapor feed type requires a vaporizer and a blower to deliver the vaporized
fuel from the vaporizer to the fuel cell body through a pipe. This procedure is prone to
heat energy loss. Besides, the combined vaporizer-blower-pipe makes the fuel cell bulky
and heavy.
- 16 (3) The vaporous fuel at a higher temperature means a faster and more efficient catalytic
reaction at the anode catalyst site. This reaction condition promotes essentially full
conversion of the fuel into the desired electrons and protons, thereby minimizing
methanol crossover from the anode to the cathode side through the electrolyte. A reduced
methanol crossover implies not only a higher electro-oxidation of methanol-water fuel at
the anode, but also less methanol “poisoning” of the cathode catalyst which allows better
contacts between oxygen and the cathode catalysts.
- 21 (4) The liquid fuel feeding via capillarity pressure-driven diffusion of liquid fuel through the
anode makes it possible to have a highly compact fuel cell assembly due to the fact that
no liquid fuel pump or vapor fuel blower is needed in the LVFC.

The above extrinsically controlled LVFC, in practice, needs a temperature sensor, a heating
element, and a simple temperature-controlling circuit. The intrinsically controlled LVFC has the
following added advantage:

- 26 (5) The fuel cell geometry (size and shape) and material compositions involved can be
selected in such a manner that the methanol-water fuel is in a vaporous state locally at the
anode catalyst phase, but in a liquid state at other locations of the anode side. The needed
heat comes primarily from the inherent electrode reactions. This feature will allow an
intrinsically controlled LVFC to enjoy the same advantages (3) and (4) cited above for the

1 extrinsically controlled LVFC, but without having to implement a temperature sensor,
heater, and temperature controlling circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG.1 A cross sectional view showing the components of a prior-art fuel cell that operates on
fuel vapor.

6 FIG.2 A cross sectional view showing the structure of the components of a fuel cell containing
anode catalysts that operate locally on a fuel vapor or vapor-liquid mixture.

FIG.3 A perspective view showing the components of the fuel cell of the present invention.

FIG.4 A cross sectional view showing the structure of the components of a fuel cell wherein the
anode contains a heating element to help vaporize the fuel.

11 FIG.5 The voltage-current responses of two fuel cells.

DETAILED DESCRIPTION OF THE INVENTION

In order to best illustrate the features and advantages of the presently invented fuel cells,
relevant prior-art fuel cells will be briefly discussed first. An example of prior-art fuel cells that
operate on organic fuel vapor is presented in FIG.1 (Tomimatsu, et al., U.S. Pat. No. 6,447,941,
16 Sep. 10, 2002). This cross sectional view of the structure includes an electrolyte plate 1, which is
held between a fuel electrode (anode) 2 and an oxidant electrode (cathode) 3. The electrolyte
plate 1, the anode 2, and the cathode 3 constitute the power generating section 4. The anode 2
and the cathode 3 are made of an electrically conductive porous material so that they allow the
passage of fuel and oxidant gas as well as electrons.

21 This prior-art fuel cell contains a fuel-permeating layer 6 and a separate fuel evaporating
layer 7. Layer 6 introduces liquid fuel into the fuel cell by the capillary action. The fuel
evaporating layer 7 is interposed between the anode 2 and the liquid fuel-permeating layer 6.
Layer 7 evaporates the liquid fuel which is introduced into the fuel cell and feeds the fuel in the
form of vapor to the anode 2, which is another separate layer. Layers 2, 1, and 3 together form a
26 power-generating section 4. Layers 3, 1, 2, 7, 6 together constitute a "unit cell". Several of these
unit cells are placed on top of another consecutively, with a separator 5 interposed between them,

1 so that they constitute a stack 9 which is the fuel cell proper. The grooves 8 through which the
oxidant gas is supplied are formed continuously in that surface of the separator 5 which is in
contact with the cathode 3.

It is clear that this prior-art fuel cell, although much simplified over other existing fuel
cells, still has a relatively complex configuration and has too many layers. By contrast, we have
6 integrated the fuel-permeating layer, the fuel evaporating layer, and the anode layer into just one
anode layer 12 (FIG.2). Preferably, the catalyst phase in the anode layer 12 is arranged to be in a
close proximity to or in an intimate contact with the electrolyte layer 11. The catalyst phase may
be essentially a thin layer (of a nanometer thickness) at the edge of the anode layer 12 facing the
electrolyte layer 11. In such an arrangement, the reaction heat generated by the inherent electro-
11 chemical reactions can easily reach the catalyst phase to help vaporize the fuel that has permeated
to the vicinity of the catalyst. It is not necessary to vaporize all the liquid fuel that has permeated
into the anode layer, only the portion close to or in contact with the catalyst (hence, the name
“local vapor fuel cell”).

It may be noted that, in the aforementioned prior-art fuel cell (FIG.1), the fuel permeating
16 layer 6 is isolated or separated from the reaction electrodes in such a distance that it cannot
effectively receive the reaction heat generated by the cell reactions. The prior-art inventors also
failed to recognize that a fuel vapor-liquid mixture works nearly as well as a pure vapor in the
anode reaction for proton production, which we surprisingly found to be the case. It is desirable
to select the electrolyte layer thickness and other reaction conditions such that the catalyst phase
21 is heated by the reaction heat to a temperature significantly higher than 64°C (the boiling point of
methanol) in the case of using methanol/water mixture as the liquid fuel. The local reaction
temperature at the anode catalyst for the methanol fuel cell is preferably in the range of 80-
150°C, but most preferably in the range of 95-130°C. Although a higher temperature is generally
26 preferred for a higher efficiency, an excessively high local temperature can spill over to other
portions of the anode, making it more difficult to maintain the fuel in other portions of the anode
(than the catalyst layer area) in a liquid state.

1 Alternatively, one may choose to introduce a thin metal wire or conductive fiber (e.g., 24
in FIG.4) into the catalyst side of the anode layer to help vaporize the liquid fuel in the vicinity of
the catalyst phase (26 in FIG.4). A small amount of current may be allowed to flow through this
wire or fiber to produce joule heat. A minute temperature sensor element (e.g., a thin
thermocouple wire) may be placed inside the anode to monitor the catalyst phase temperature.
6 Temperature monitoring and control devices or circuits are well-known in the art. Such a
combined heating element-sensor arrangement is advantageous in that additional heat may be
supplied to vaporize more fuel on demand (e.g., when needed, more current may be supplied to
the external load by vaporizing the fuel at a faster rate and allowing the reactions to proceed at a
higher temperature). With such an added adaptability, the fuel cell essentially becomes a smart,
11 actively controlled power source. A simple logic circuit may be added as a part of the fuel cell
voltage regulator or control circuit that is normally installed in a fuel cell for electronic device
applications.

 In one special fuel cell design of Tomimatsu, et al., there is a combined fuel permeating-
evaporating member, which has a fuel permeating portion and a fuel evaporating portion.
16 However, this combined layer has to be made to contain specially machined holes and are
complex in configuration. This requirement makes this layer and the whole fuel cell assembly
more difficult and costly to produce despite the notion that this combination makes it possible to
decrease the thickness of the member, as compared with the case where each of these fuel
permeating member and the fuel evaporating member are formed of individual members
21 separately.

 As a means to feed liquid fuel to the anode layer 12 from a fuel source, there is formed a
liquid fuel passage 20 along at least one side of the stack 19 (FIG.2). Upon introduction into the
liquid fuel passage 20, the liquid fuel is fed to the fuel permeating material of the anode layer 12
by the capillary action from the side of the stack 19. In order to supply liquid fuel to the fuel
26 permeating material by the capillary action, the fuel cell is constructed such that the liquid fuel
which has been introduced into the liquid fuel passage 20 comes in direct contact with the end
surface of the anode layer 12.

1 The separator **15** (when existing) and the anode layer **12** (including the fuel permeating
material therein) are each made of an electrically conductive material so that they function as a
current collector to transmit electrons generated in the fuel cell. The fuel cell in this example
(FIG.2) has the separator **15** which functions also as a channel to permit the oxidant gas to flow
therethrough into the cathode. The advantages of using the multi-purpose separator **15** include a
6 size reduction and reduction in the number of parts used.

 The liquid fuel passage **20** may be constructed such that the liquid fuel is introduced from
a fuel source (not shown) into the fuel permeating material of the anode layer **12** by the capillary
action. One way to supply liquid fuel from the fuel source to the liquid fuel passage **20** is to
permit the liquid fuel to drop spontaneously by gravity and to enter the liquid fuel passage **20**.
11 This gravitational method offers the advantage of assuring the introduction of the liquid fuel into
the liquid fuel passage **20**, although it requires that the fuel source be positioned above the top of
the stack **19**. Another method is to introduce the liquid fuel from the liquid fuel source by the
capillary action of the liquid fuel passage **20**. This method does not require that the joint between
the liquid fuel source and the liquid fuel passage **20** (or the fuel entrance of the liquid fuel
16 passage **20**) be arranged above the top of the stack **19**. When combined with the gravitational
method, this method offers the advantage of being free to install the fuel source at any place or
orientation. The liquid fuel passage **20** may be formed on one side or both sides of the stack **19**.

 The fuel source described above may be made detachable from the fuel cell proper, so
that the fuel cell can be run for a prolonged period of time by intermittently replenishing the fuel
21 source. The feeding of the liquid fuel from the fuel source to the liquid fuel passage **20** may be
accomplished by gravity or by pressure in the source. An alternative feeding method is to extract
the liquid fuel by the capillary action of the liquid fuel passage **20**.

 The structure of the fuel permeating material in the anode layer is not specifically
restricted as far as it permits the liquid fuel to permeate through it by the capillary action. It may
26 be made of a porous material, cotton, non-woven fabric, highly porous paper, or woven cloth of
fibers. The fuel permeating material draws liquid fuel into it by the capillary action. For the

1 effective use of the capillary action, the fuel-permeating porous material should be formed such
that its pores are interconnected and its pores have an adequate pore diameter. The porous
material may have any pore diameter which is not specifically restricted, as long as it permits the
liquid fuel to be drawn into the liquid fuel passage 20. However, the pore diameter is preferably
0.01 to 150 μm in view of the capillary action of the liquid fuel passage 20. Furthermore, the
6 pore volume as an index of pore continuity should preferably be 20 to 90% of the porous
material. With a pore diameter smaller than 0.01 μm , it becomes difficult for liquid fuel to
diffuse through the pores; this could be understood from the well-known Darcy's Law that
describes the diffusion behavior of a liquid through a porous medium. With a pore diameter
larger than 150 μm the porous material is poor in its capillary action. With a pore volume less
11 than 20%, the porous material has closed pores in a higher proportion and hence is poor in its
capillary action. With a pore volume fraction greater than 90%, the porous material has a higher
proportion of continuous pores but is poor in strength and present difficulties in fabrication.
Practically, the pore diameter should preferably be 0.5 to 100 μm and the pore volume fraction
should preferably be 30 to 75%.

16 Liquid fuel feeding grooves 21 may be formed in the surface of the separator 15 (serving
also as the channel) in contact with the fuel permeating material of the anode layer 12, as shown
in FIG.3. The capillary action of these grooves may be used to draw liquid fuel into the fuel
permeating material also through the capillary action. In this case, the liquid fuel passage 20
should be formed such that the open ends of the liquid fuel feeding grooves 21 come into direct
21 contact with the liquid fuel passage 20 (indicated in FIG.2, but not FIG.3). Alternatively, it is
possible to use the capillary action of the liquid fuel feeding grooves 21 in combination with the
capillary action of the porous material constituting the fuel permeating material of the anode
layer 12.

26 It may be noted that the liquid fuel feeding grooves 21 are not specifically restricted in
configuration as long as they are capable of producing an adequate capillary action. However,
they should be formed such that their capillary action is smaller than that of the fuel permeating
material of the anode layer. Otherwise, the liquid fuel will not be fed from the liquid fuel passage

1 20 to the fuel permeating material. The liquid fuel feeding grooves 21 are intended to extract
liquid fuel from the liquid fuel passage 20 by their capillary action. Therefore, they should be
formed such that their capillary action is greater than that of the liquid fuel passage 20 in the case
where the liquid fuel is introduced from the fuel source into the liquid fuel passage 20 by its
capillary action. Thus, the configuration of the liquid fuel feeding grooves 21 should be formed
6 in accordance with the configurations of the porous material constituting the fuel permeating
material of the anode layer 12 and the liquid fuel passage 20.

The separator 15 serving also as the channel is provided with the liquid fuel feeding
grooves 21 extending in the horizontal direction, as mentioned above. This construction permits
the liquid fuel to be fed from the entire surface of the end of the anode 12 to the fuel permeating
11 material inside the anode layer and also permits the liquid fuel to be fed in the lateral direction
across the anode layer through the grooves 21. This makes it possible to feed liquid fuel more
smoothly from the liquid fuel passage 20 to the fuel permeating material.

In the aforementioned example, the separator 15 serving also as the channel is provided
with both the oxidant gas feeding grooves 18 and the liquid fuel feeding grooves 21.
16 Alternatively, the anode layer 12 and the cathode 13 may be individually provided with channels.
In this case, one set of channels should be separated from another set of channels by an
electrically conductive plate to block the passage of gas, or the holes on the surface of at least one
set of channels should be closed, so that the liquid fuel is separated from the oxidant gas. In order
to decrease the number of parts used and to reduce the size of the fuel cell, it is desirable to use
21 the separator containing both types of channels.

The examples described above are directed to a fuel cell which has the stacks 19 (each
composed of a power generating section 14) which are placed on top of the other, with each stack
separated by the separator 15. However, the fuel cell of the present invention does not
necessarily need the separator channels. In this case, the oxidant gas feeding grooves 18 may be
26 continuous ones formed in the surface in contact with the cathode.

1 In another embodiment of the present invention, the fuel cell may have a liquid fuel-
holding portion positioned on the anode (in contact with one of the two primary or larger-area
surfaces of the anode, rather than on one end or both ends of the anode). In this case, the fuel cell
comprises (a) a cathode, (b) an electrolyte plate disposed on the cathode, (c) an anode disposed
on the electrolyte plate and configured to be supplied with a liquid fuel, and (d) a liquid fuel-
6 holding portion disposed on the anode. The anode is provided with a heating environment to at
least partially vaporize the liquid fuel inside the anode and the anode further comprises a catalyst
phase to ionize the fuel in a vapor or vapor-liquid mixture form to produce protons. Other
features and operating methods of this fuel cell are similar to those discussed earlier in other
embodiments.

11 Example 1

A fuel cell was prepared as follows: Graphite flakes were subjected to a ball-milling
treatment to obtain fine particles of several microns in size. These fine particles were mixed with
a phenolic resin to obtain a slurry mixture. Chopped carbon fibers were then mixed with the
slurry mixture to prepare a composite, which was then molded at a temperature of 250°C for one
16 hour with a hot press and then partially carbonized first at 350°C and then at 600°C for
approximately two hours. These treatments lead to the formation of a thin, highly porous carbon
structure having an average pore diameter of 60 μm and a porosity of approximately 65%. A
sheet of this carbon composite structure was coated on one side with a Pt-Ru catalyst to give an
anode of 32 mm x 32 mm in dimensions. A carbon cloth was coated with a platinum black
21 catalyst to give a cathode also of 32 mm x 32 mm. A polymer electrolyte membrane,
poly(perfluorosulfonic acid) ionomer, was held between the anode and the cathode, with the
catalyst layers in contact with the electrolyte membrane. The assembly was joined together by
hot-pressing at 120°C for 5 minutes under a pressure of 100 kg/cm², to give a power generating
section. The resulting assembly was held between a cathode holder and an anode holder, the
26 former having oxidant gas feeding grooves each having a depth of 2 mm and a width of 1 mm.
The obtained unit cell has a reaction area of 10 cm². The fuel cell was supplied with a
methanol/water mixture at an 1:1 molar ratio as a liquid fuel. The liquid fuel was introduced by
the capillary action through the side of the anode. The air at 1 atm as an oxidant gas was fed into

1 the gas channels at a flow rate of 100 mL/min so that the fuel cell generated electricity at 76°C.
This fuel cell gave a current-voltage characteristic as shown in Curve A of FIG.5.

Comparative Example 1

6 A fuel cell of the prior-art type was prepared as follows. An assembly for the power
generating section was prepared in the same way as in Example 1. However, the power
generating section was further combined with a fuel evaporating layer and a fuel permeating
layer as shown in FIG.1. The fuel evaporating layer is a porous carbon plate having an average
pore diameter of 100 μ and a porosity of 70%. The fuel permeating layer is a porous carbon plate
having an average pore diameter of 5 μ m and a porosity of 40%. The liquid fuel cell thus
obtained was supplied with a methanol-water mixture mixed at a 1:1 molar ratio as a liquid fuel.
11 The liquid fuel was introduced by the capillary action through the side of the anode. The air at 1
atm as an oxidant gas was fed into the gas channels at a flow rate of 100 mL/min so that the fuel
cell generated electricity at 79°C (measured at the catalyst/electrolyte interface). This fuel cell
gave a current-voltage characteristic as indicated in Curve B of FIG.5.

16 The two curves shown in FIG.5 demonstrate that the fuel cells in both examples produce
a stable output voltage until the current reaches about 5 amps. This implies that it may not be
necessary to have separate liquid fuel-permeating and fuel-vaporizing layers (that would make
the fuel cell more bulky, heavy and expensive). It appears that as long as the catalyst phase
works primarily with a fuel vapor, the fuel cell is capable of achieving a high reactivity and low
methanol cross-over (from the anode to the cathode side).

21 Example 2

26 A series of fuel cells were prepared and operated in the same way as in Example 1, with
the exception that a thin copper wire was introduced into and out of the anode at a location very
close to the polymer electrolyte layer (and, hence, close to the catalyst layer). A desired amount
of current was fed into this zone to vary the fuel temperature between approximately 64°C (the
boiling point of methanol) and 130°C (30° above 100°C, the boiling point of water) while the
exterior temperature was maintained at a relatively low level by blowing a cool air to the fuel cell

1 while in operation. It was found that, in general, the higher the reaction temperature, the more
stable the voltage was. A higher local temperature near the catalyst phase implies not only a
higher vapor content, but also a higher electrolytic reaction rate at the anode (Reaction 1). Both
factors are in favor of a more stable voltage response as a function of current by way of an
increased reactivity (faster and more efficient fuel conversion) and reduced chance of fuel cross-
6 over.

It may be noted that, although the examples given herein are based on the methanol/
water mixture as the liquid fuel, the presently invented fuel cell is not limited to this particular
type of fuel. The present fuel cell can operate on any organic fuel that has a high hydrogen
content (e.g., ethanol and hexane) and can be fed in a liquid form into the anode through
11 diffusion and then vaporized locally at the catalyst phase. For instance, the ethanol/water
mixture can be used in the fuel cell when the catalyst zone is heated to a temperature above 78°C,
up to approximately up to 130°C with poly(perfluorosulfonic acid) being the PEM used. This
upper temperature appears to be limited by the working temperature of the polymer electrolyte.
With a more thermally stable polymer electrolyte membrane, such as sulfonated polyimide, the
16 vapor fuel temperature can be pushed even higher. A temperature up to 150°C (approximately
50 degrees above the boiling temperature of water) was found to work well.

Hence, another embodiment of the present invention is a fuel cell which comprises (A) an
anode comprising a catalyst phase and receiving a liquid fuel from a liquid fuel source (with the
liquid fuel having a minimum boiling point $T_b(\text{min})$ and a maximum boiling point $T_b(\text{max})$); (B)
21 an ion exchange electrolyte having a first surface adjacent to the anode; and (C) a cathode
adjacent to a second surface of the electrolyte. In this fuel cell, the anode is provided with a
heating environment inside the anode to ensure that the catalyst phase operates at a temperature
between $T_b(\text{min})$ and approximately $[T_b(\text{max}) + 50 \text{ degrees C}]$ to ionize the fuel to produce ions
that move across the ion exchange electrolyte.

26 It is known that water has a boiling point of 100°C, methanol has a boiling point of
approximately 64°, and ethanol has a boiling point of approximately 78.5°C. For a fuel cell fed

1 with a mixture of water and methanol, the catalyst phase operates on methanol in a vaporous
state and water in substantially liquid state if the local temperature is in the range of 64°C and
100°C. Both methanol and water will be substantially vaporized if the catalyst temperature
exceeds 100°C. It is particularly advantageous to allow the catalyst phase to operate at a local
6 temperature of slightly higher than 100°C, but preferably not higher than 130°C with an ion
exchange electrolyte comprising poly(perfluorosulfonic acid) as the primary ion-conducting
medium. For the ethanol/water mixture, the catalyst operating temperature is in the range of
78°C and 150°C, but preferably in the range of 100°C and 130°C. For a three-component
mixture (water + methanol + ethanol), the catalyst operating temperature is in the range of 64°C
and 150°C, preferably in the range of 78°C and 130°C, but most preferably between 100°C and
11 130°C.